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STRUCTURE FUNCTION MEASUREMENTS AND POLARISED CROSS SECTION MEASUREMENTS FROM HERA

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ABSTRACT

Recent measurements of inclusive and semi-inclusive measurements from the HERA collaborations are presented. The measurements include neutral current structure functions F_2 , F_L and xF_3 ; the charged current cross section including first measurements of the dependence on electron polarisation; and measurements of the heavy quark structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$.

1 Introduction

Deep inelastic scattering (DIS) has long been used to measure the structure of hadrons. Measurements with a fixed target helped establish the quark parton model and the theory of the strong force, quantum chromodynamics (QCD). HERA, being the first colliding beam DIS experiment, enables proton structure to be measured in hitherto unexplored regions. The measurements of proton structure at HERA, particularly at very low fractional parton momentum, have yielded extremely precise parton distribution functions (PDFs), essential for making QCD predictions at present and future hadron colliders.

In the years 1998–2000 HERA was operated in both e^+p and e^-p scattering modes at a centre of mass energy of $\sqrt{s} = 320$ GeV. The large data samples collected has allowed a determination of all the possible neutral current (NC, $ep \rightarrow eX$) structure functions F_2 , F_L and xF_3 for the first time at HERA. The structure function F_2 is sensitive to all quark species and dominates the cross section throughout the accessible phase space. The quantity xF_3 is sensitive to the valence quarks. Since the cross section only becomes sensitive to xF_3 via the exchange of the Z^0 boson, its influence is limited to the very high Q^2 electroweak regime. Finally, F_L is sensitive to higher order gluon radiation processes providing valuable confirmation of the gluon content of the proton.

Like the neutral current cross section, the charged current (CC, $ep \rightarrow \nu X$) cross section is an important tool to measure the structure of the proton, particularly since the charged current process is sensitive to the quark flavour decomposition of the proton. Measurements of the e^+p and e^-p scattering cross sections have allowed independent determination of the u quark and d densities. In the years 2003–2004 HERA operated in e^+p mode with longitudinally polarised e^+ beam, allowing the dependence of the CC cross section on polarisation to be measured for the first time.

The structure functions are usually presented in terms of the kinematic variables Bjorken x , the fraction of the proton’s momentum carried by the struck quark and Q^2 the negative square of the 4-momentum transfer of the exchanged boson. Q^2 may be interpreted as the resolving power of the exchange, with increasing Q^2 able to resolve smaller distances within the proton. They may be derived from the differential cross sections as

$$\frac{d\sigma_{NC}(e^\pm p)}{dx dQ^2} \simeq \frac{2\pi\alpha^2}{xQ^4} [Y_+ \tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2 \tilde{F}_L] \quad (1)$$

Here α is the electromagnetic coupling constants and $Y_\pm = 1 \pm (1 - y)^2$

where $y = Q^2/sx$. A similar relationship holds for CC interactions [1].

2 Proton Structure at Low x

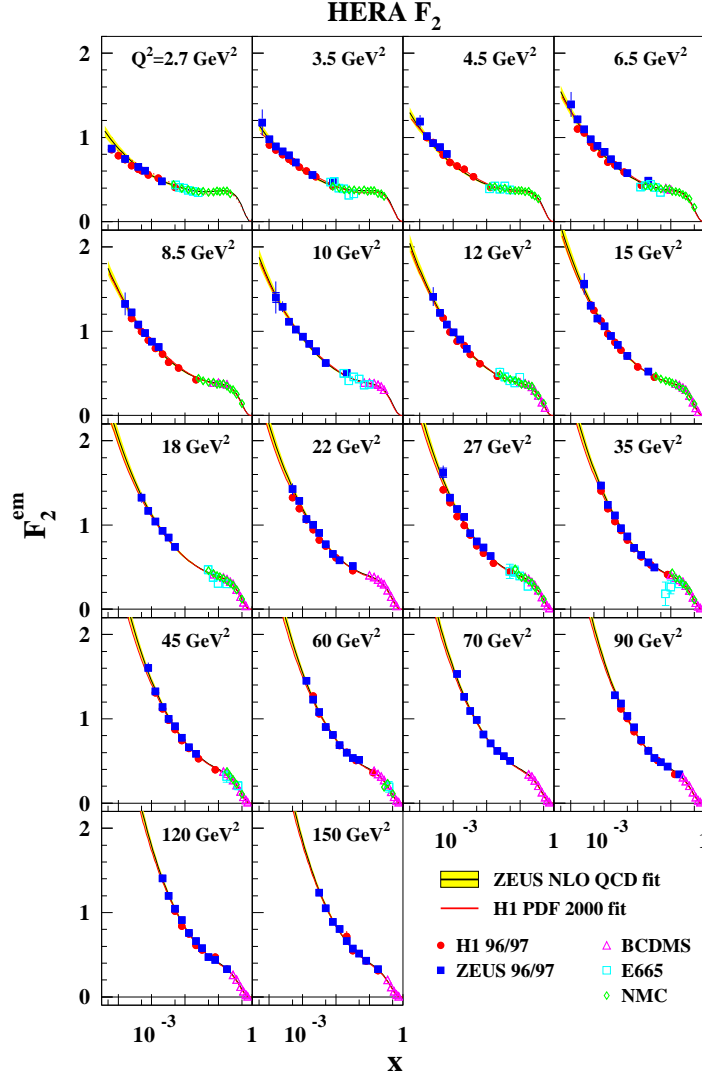


Figure 1: *Measurements of the structure function F_2 from the HERA collaborations and fixed target experiments. The data are plotted as a function of x for various fixed values of Q^2 . Also included are the results of a NLO QCD fit to the data.*

The large integrated luminosity achieved by HERA in the last few years has provided data samples of several million events for NC measurements at low x and low Q^2 . This has allowed the determination of the proton structure function F_2 to an accuracy of $\simeq 2\%$ [2, 3]. Example measurements of F_2 from HERA and

fixed target experiments are shown in figure 1. F_2 , which is sensitive to the total quark density of the proton, is seen to rise steeply as x decreases. The data are compared to a next to leading order (NLO) quantum-chromodynamics (QCD) fit, which describes all data for $Q^2 > 3$ GeV very well.

It may also be seen in figure 1 that the rise towards lower x becomes more pronounced as Q^2 increases. In order to explore this feature more quantitatively F_2 is parameterised as $F_2 = c(Q^2)x^{-\lambda}$ and the slope parameter λ is plotted as a function of Q^2 in figure 2. For $Q^2 > 1$ GeV it can be seen that λ increases. This can be explained by the fact that as Q^2 increases the resolving power of the probe increases and more and more splitting processes of the form $g \rightarrow q\bar{q}$ are resolved. The components after the spitting carry less momentum and so are observed at lower x . At $Q^2 < 1$ GeV the data tend to reach a constant value for λ . In this region the data are difficult to describe using perturbative QCD although non-perturbative models do have some success [4].

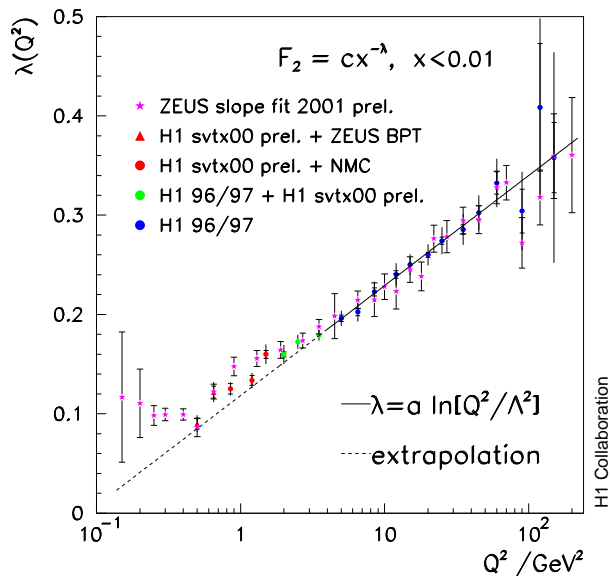


Figure 2: Measurements of the slope parameter λ where the F_2 is parameterised as $F_2 = c(Q^2)x^{-\lambda}$.

It is also interesting to plot F_2 as a function of Q^2 at fixed x as shown in figure 3.(a). If the proton were made solely of 3 quarks F_2 should remain constant or scale with Q^2 . What is seen is negative scaling violations at large x , approximate scaling at $x \simeq 0.2$ and very large positive scaling violations at low x . In QCD these scaling violations are interpreted as gluon radiation. As Q^2 increases there is an increasing chance that a valence quark radiates a gluon and so decreasing the quark

density at higher x . Conversely at lower x there is an increased chance of a radiated gluon splitting into a quark pair so the density increases.

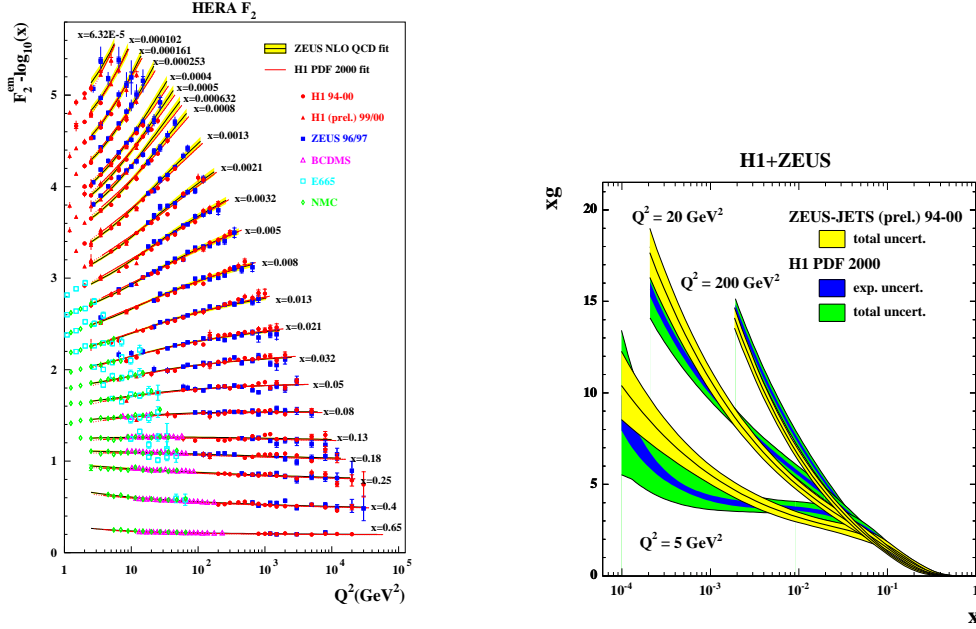


Figure 3: (a) Measurements of the structure function F_2 from the HERA collaborations and fixed target experiments. The data are plotted as a function of Q^2 for various fixed values of x . Also included is the results of a NLO QCD fit to the data. (b) The gluon density derived from the NLO QCD fit, plotted as a function of x for various Q^2

NLO QCD theory shows that the gluon density is related to the differential of F_2 : $dF_2/dQ^2 \propto xg$. Such a determination has been performed and the results are shown in figure 3.(b). Similar scaling violations are observed to the quark density of the proton.

3 Determination of the longitudinal structure function F_L

The structure function F_L has not been directly determined at HERA since a run taken at lower beam energies has not yet been performed. The data, however, are sensitive to F_L at high y as can be seen by examining equation 1. H1 have used the approach that since F_2 is well determined over a wide range of x and Q^2 it may be extrapolated into the region at high y using the QCD fit [2, 5]. Thus, by subtracting a term that depends on F_2 and making a very small correction for xF_3 one may determine F_L . Such a determination is shown in figure 4 for various different Q^2 and x for a fixed $y = 0.75$. Measurements from the e^+p data and

the e^-p data are shown. It can be seen that the data are inconsistent with either $F_L = 0$ or $F_L = F_2$. The NLO QCD fit shows good agreement to the data. This is an important test of QCD since F_L only arises through higher order corrections. Measurements have also been made at lower Q^2 [2] which also show agreement to the theory.

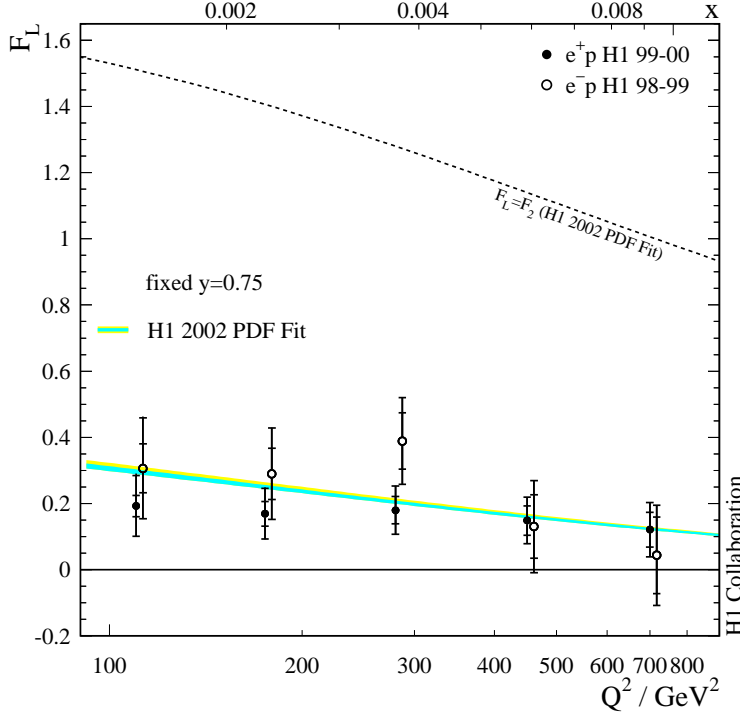


Figure 4: Determination of the structure function F_L . The data are plotted as a function of Q^2 and x for a fixed values of y . Measurements from the e^+p data and the e^-p data are shown. The data are compared to the results of the NLO QCD fit. The 2 extreme possibilities $F_L = 0$ and $F_L = F_2$ are also shown.

ZEUS have made a direct measurement of F_L using events where the incoming e^+ radiates a photon, so decreasing the centre of mass collision energy. Although the errors on the first measurement are large it shows that the method works and reduced errors may be possible with high luminosity HERA II running.

4 Neutral and Charged Current Cross Sections at high Q^2

The NC and CC single differential cross sections $d\sigma/dQ^2$ at high Q^2 are shown in fig. 5 for both e^+p and e^-p scattering [5, 6, 7]. The NC data are seen to fall with the typical $1/Q^4$ behaviour as expected for a photon propagator. The CC cross section

is suppressed at low Q^2 due to the large W boson mass. At $Q^2 > M_W^2$ the cross sections become comparable as expected from the unification of the electroweak force. The measurements are compared to a NLO QCD fit which provides a good description of the data.

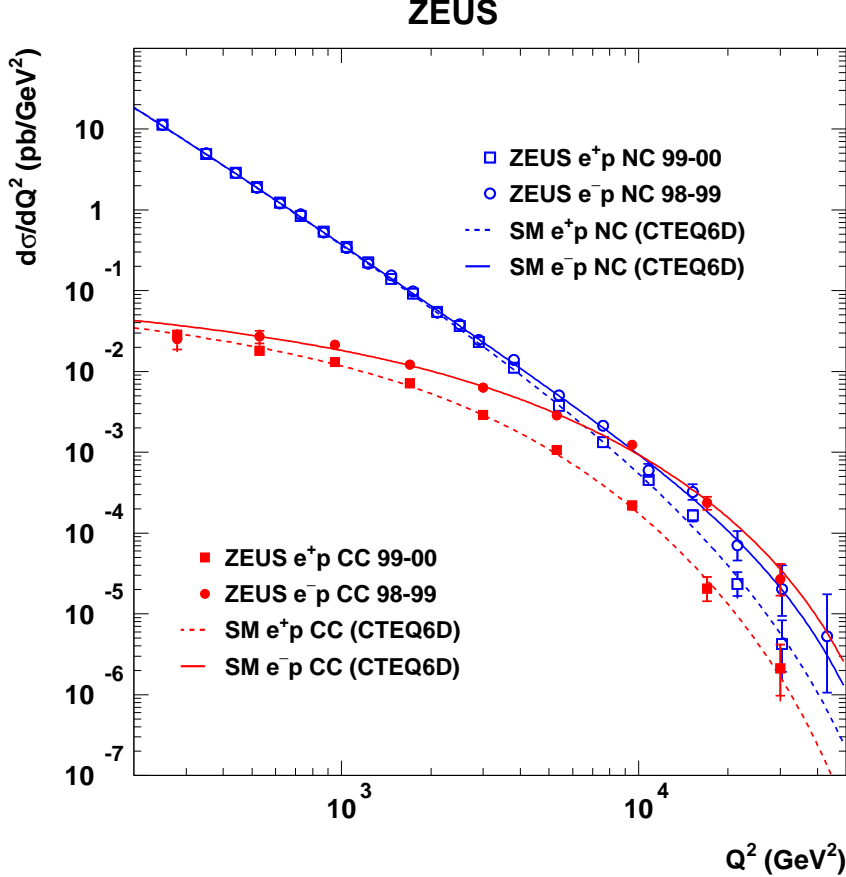


Figure 5: The Q^2 dependences of the NC (circles) and CC (squares) cross sections $d\sigma/dQ^2$ are shown for the combined 94 – 00 e^+p and 98 – 99 e^-p measurements. The data are compared to the Standard Model expectations determined from a NLO QCD fit.

The combination of four cross sections, NC and CC in both e^+p and e^-p scattering, allows the flavour separation of the proton to be achieved with minimal assumptions using HERA data alone for the first time. NLO QCD fits have been made by both collaborations to this data taking into account experimental and theoretical uncertainties [5, 8]. ZEUS include their jet data in order to reduce uncertainties particularly in the medium x region ($x_{simeq}0.1$), where the HERA

inclusive data do not constrain the gluon very precisely. The results of these fits are shown in fig. 6 for the u and d valence quark densities xu_v , xd_v ; the sea quark density xS and the gluon density xg . The results of the two fits agree well.

The cross section measurements has been improved through a reduction of the systematic uncertainties which dominate the NC measurement up to $Q^2 \simeq 1000 \text{ GeV}^2$. The double differential NC cross section now has a total systematic uncertainty of typically about 3% compared to 6% previously. This reduction in the systematic uncertainty has allowed the u density to be determined to a precision of typically 3%, and the d density with a precision of 10% at $x = 0.4$.

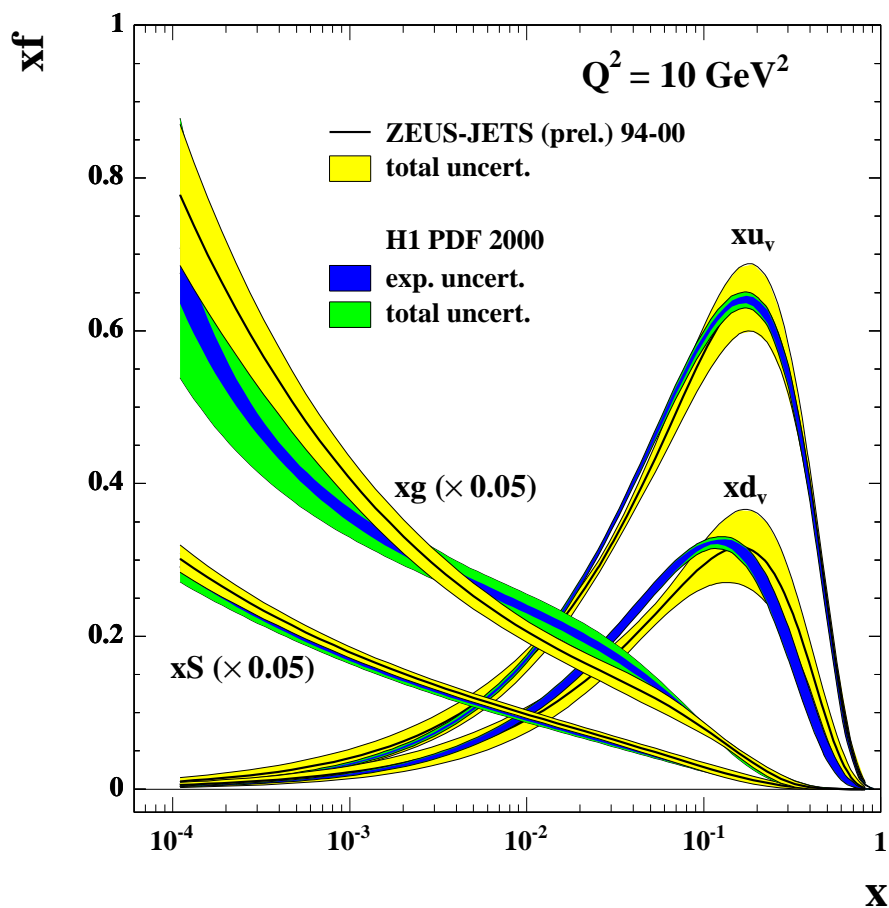


Figure 6: The parton distributions as determined from the H1 PDF 2000 fit to H1 inclusive data only and those from the ZEUS-JETS fit to ZEUS inclusive and jet data. The distributions are shown at $Q^2 = 10 \text{ GeV}^2$.

5 Measurement of the structure function xF_3

From equation 1 it can be seen that the structure function xF_3 may be measured by subtracting the e^+p NC data from the e^-p data. Although xF_3 only becomes a non-negligible part of the cross section at large Q^2 when $Q^2 \simeq M_Z^2$ there are now enough statistics for a first measurement from HERA. This is shown in figure 7. The structure function xF_3 is particularly important because it is only sensitive to the valence quarks. The measurements from HERA show good agreement to the NLO QCD fit. The excess seen at low x is not significant due to the relatively large errors on the data at the moment.

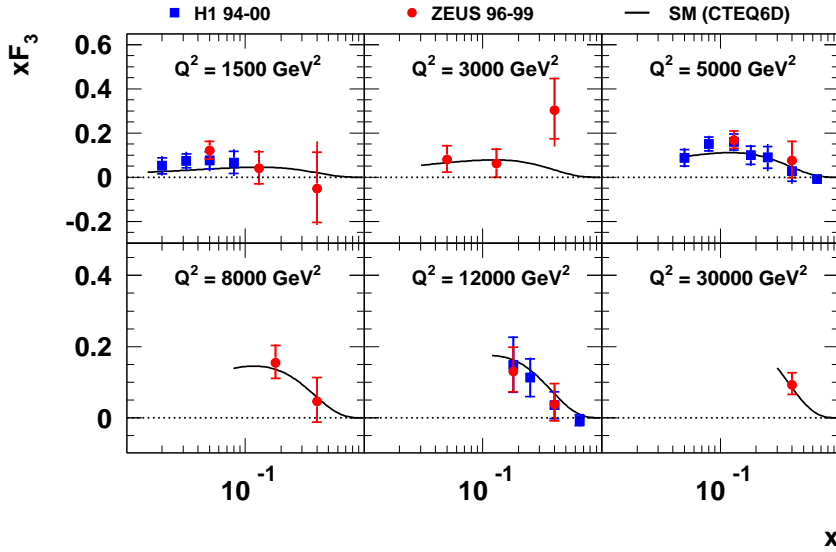


Figure 7: Measurements of the structure function xF_3 . The data are plotted as a function of x for various fixed values of Q^2 . Also included is the results of a NLO QCD fit to the data.

6 Polarised CC cross section

The HERA upgrade included installation of spin rotators in the HERA ring. This enables longitudinal polarisation of the e^+ beam. The first measurements [9] of the CC cross section as a function of polarisation (P) are shown in figure 8. It is seen that the cross section is smaller for negative polarisation than for positive. In the Standard Model, due to the absence of right handed charged currents, it is expected that the CC cross section follows a linear dependence, with zero expectation at $P = -1$. The Standard Model agrees well with the data.

HERA II

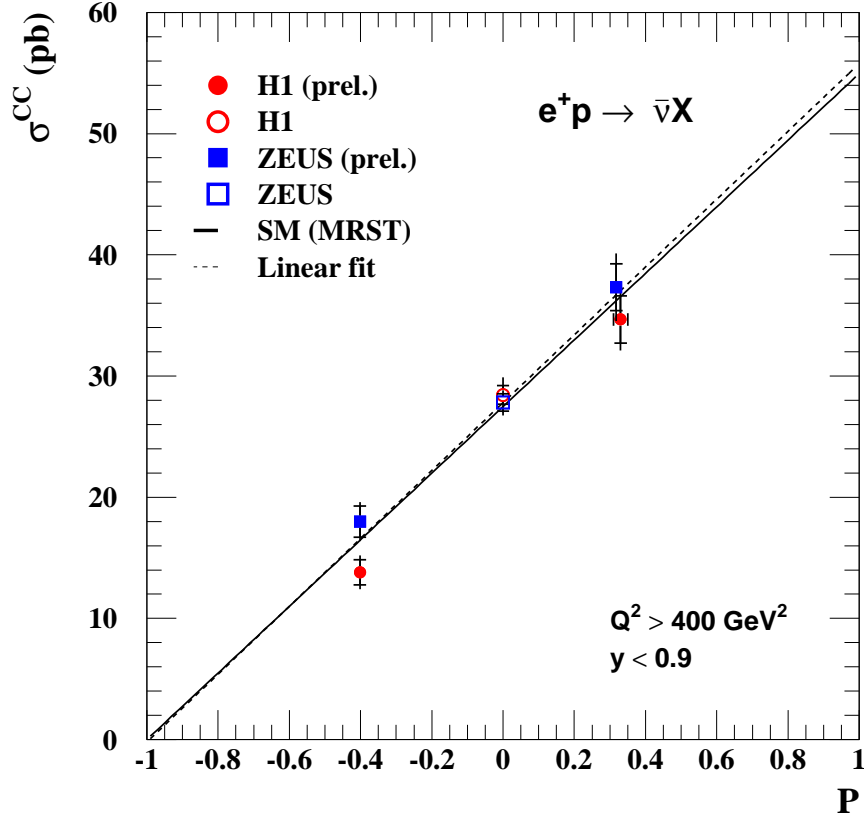


Figure 8: Measurements of the CC cross section as a function of the longitudinal polarisation of the the e^+ beam.

7 Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

There have been 2 methods employed at HERA to extract the charm and beauty structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ of the proton. The first method is to tag charm by reconstructing D^* mesons. This method results in a clean high statistics event sample and has been used by H1 and ZEUS to measure $F_2^{c\bar{c}}$ over the range $2 < Q^2 < 500 \text{ GeV}^2$ [10]. The drawback of this method is that only a small fraction of charm events are seen and model dependent corrections must be employed to correct for unseen phase space, particularly at low transverse momentum of the D^* , in order to extract $F_2^{c\bar{c}}$. In the second method charm and beauty events are distinguished from each other and from the light quarks by measuring the displacement of tracks from the primary vertex [11]. The longer lived heavy hadrons produce tracks with significant displacements from the primary vertex, while the light hadrons usually decay so fast that the tracks are produced at the primary vertex. This method is used to measure $F_2^{c\bar{c}}$ and to make the first measurement of $F_2^{b\bar{b}}$. The measurements of the structure functions are shown in figure 9 for the high Q^2 region. The 2 methods used to extract $F_2^{c\bar{c}}$ are found to be in good agreement. The measurements are also compared to the predictions of NLO QCD, which is found to give a good description of both the charm and beauty structure functions.

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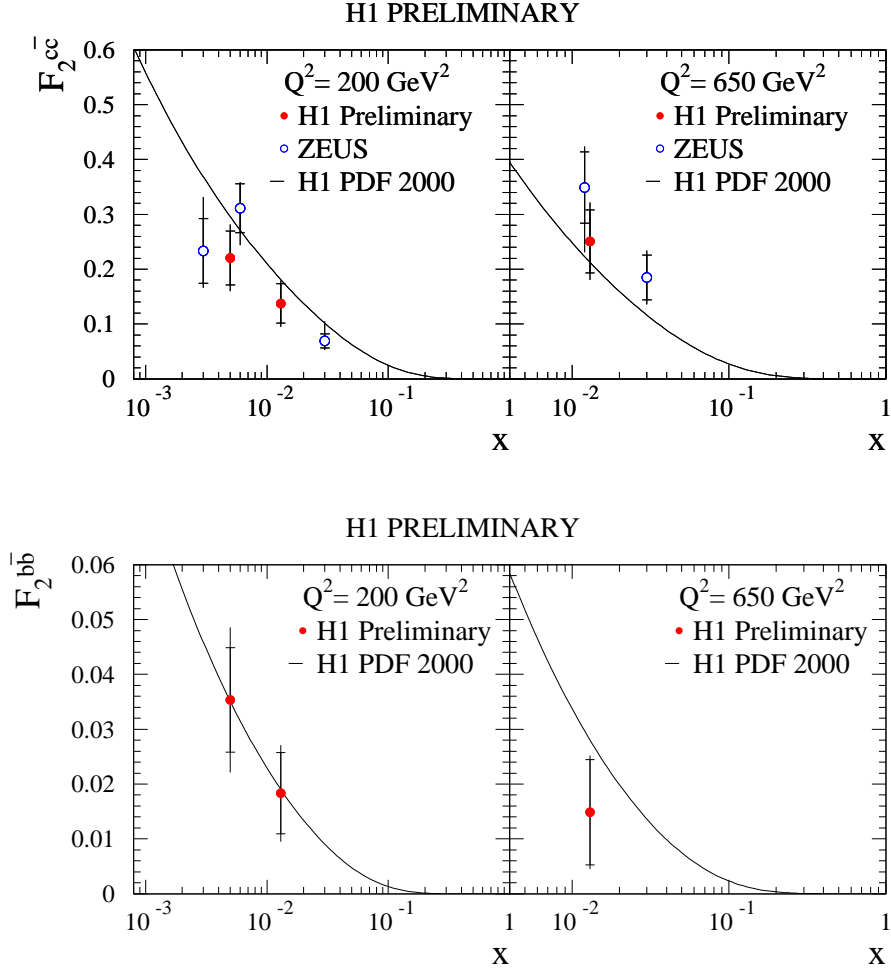


Figure 9: Measurements of the structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$. The data are plotted as a function of x for 2 values of Q^2 . Also included is the results of a NLO QCD fit to inclusive data.

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